DECISION FEEDBACK EQUALIZATION PRE-PROCESSOR WITH TURBO EQUALIZER

TO WHOM IT MAY CONCERN:

BE IT KNOWN THAT FLETCHER A. BLACKMON, employee of the United States Government, citizen of the United States of America, resident of Forestdale, County of Barnstable, Commonwealth of Massachusetts, has invented certain new and useful improvements entitled as set forth above of which the following is a specification:

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5   STATEMENT OF GOVERNMENT INTEREST

6   The invention described herein may be manufactured and used

7   by or for the Government of the United States of America for

8   governmental purposes without the payment of any royalties

9   thereon or therefore.

10

11   BACKGROUND OF THE INVENTION

12   (1) Field of the Invention

13   The present invention relates generally to communications

14   systems and, more particularly, to a high performance iterative

15   and adaptive equalizer/error correction decoder (turbo-

16   equalization) which is especially suitable for use in underwater

17   telemetry.

18   (2) Description of the Prior Art

19   The underwater environment provides numerous difficult

20   obstacles for acoustic communications. The ocean acoustic

21   channel produces large amplitude and phase fluctuations on

22   acoustic signals transmitted therethrough causing temporal,

23   spatial, and frequency dependent fluctuations. Multipath

24   distortion is a significant problem. Underwater regions often

25   experience high and/or variable sound attenuation. Ambient

1   ocean-noise influences the received signal-to-noise ratio and may

2   require high transmission power levels to achieve suitable ratios

3   depending on the conditions.

4   Presently utilized underwater coherent acoustic telemetry

5   systems are often able to transmit M-ary Phase Shift Keying

6   (MPSK) and M-ary Quadrature Amplitude Modulation (MQAM) signals.

7   At the receiver end, these coherent signals may be processed by

8   an adaptive multi-channel decision feedback equalizer (DFE). The

9   DFE is then usually followed by a de-interleaver and an error

10 correction decoder. The overall performance obtained by this

11 type of prior art underwater telemetry system is often

12 acceptable, but is not satisfactory in many situations. The

13 desire for performance improvement has led to higher performance

14 algorithms whose complexity is orders of magnitude greater than

15 the standard decision feedback equalizer (DFE) system followed by

16 de-interleaving and decoding.

17   Turbo equalization and turbo coding may be applied to many

18 detection and decoding problems. Turbo coding involves

19 concatenation of simple component codes with an interleaver so

20 that decoding can be performed in steps using algorithms of

21 manageable complexity. However, the complexity of prior art

22 turbo equalization increases exponentially with the number of

23 channels and/or other factors, thereby making a multichannel

24 telemetry system, as is typically utilized in underwater

25 telemetry systems, highly complex. More particularly, the

1 complexity of the prior art turbo-equalizer grows with channel

2 complexity, modulation level, and spatial and/or time diversity.

3 The complexity of a prior art turbo-equalizer is therefore

4 orders of magnitude greater than the typical DFE structure

5 discussed above.

6 The following U.S. Patents describe various prior art

7 systems that may be related to the above and/or other telemetry

8 systems:

9 U.S. Patent No. 5,301,167, issued April 5, 1994, to Proakis

10 et al., discloses an underwater acoustic communications system

11 that utilizes phase coherent modulation and demodulation in which

12 high data rates are achieved through the use of rapid Doppler

13 removal, a specialized sample timing control technique and

14 decision feedback equalization including feedforward and feedback

15 equalizers. The combined use of these techniques dramatically

16 increases data rates by one and sometimes two orders of magnitude

17 over traditional FSK systems by successfully combating fading and

18 multipath problems associated with a rapidly changing underwater

19 acoustic channel that produce intersymbol interference and makes

20 timing optimization for the sampling of incoming data impossible.

21 U.S. Patent No. 5,559,757, issued September 24, 1996, to

22 Catipovic et al., discloses an underwater acoustic telemetry

23 system that uses spatially distributed receivers with aperture

24 sizes from 0.35 to 20 m. Output from each receiver is assigned a

25 quality measure based on the estimated error rate, and the data,

1 weighted by the quality measure, is combined and decoded. The

2 quality measure is derived from a Viterbi error-correction

3 decoder operating on each receiver. The quality estimator

4 exploits the signal and noise differential travel times to

5 individual sensors. The spatial coherence structure of the

6 shallow-water acoustic channel shows relatively low signal

7 coherence at separations as short as 0.35 m. Increasing receiver

8 spacing beyond 5 m offers additional benefits in the presence of

9 impulsive noise and larger scale inhomogeneities in the acoustic

10 field. Diversity combining, even with only two receivers, can

11 lower uncoded error rates by up to several orders of magnitude

12 while providing immunity to transducer jamming or failure.

13   U.S. Patent No. 6,295,312 B1, issued September 25, 2001, to

14 Susan M. Jarvis, discloses a method and system for communicating

15 in a time-varying medium. A transmitter sends transmissions of

16 the same message data separated in time with respect to one

17 another. A single sensor receives the transmissions. Each

18 received transmission is buffered until all of the transmissions

19 that were sent are received. The buffered transmissions are

20 simultaneously processed via multichannel adaptive equalization

21 only when all of the transmissions that were sent are received.

22   The above cited prior art does not disclose a system whose

23 complexity is similar to that of the prior art decision feedback

24 equalizer followed by a de-interleaver and an error correction

25 decoder, but whose performance is comparable to telemetry systems

1 with much higher orders of complexity. The above cited prior art

2 also does not disclose lower complexity, better performing

3 telemetry system which lowers the complexity associated with

4 turbo-equalization. The solutions to the above described and/or

5 related problems have been long sought without success.

6 Consequently, those skilled in the art will appreciate the

7 present invention that addresses the above and other problems.

8

9   SUMMARY OF THE INVENTION

10   It is a general purpose of the present invention to provide

11 an improved telemetry system.

12   An object of the present invention is an improved underwater

13 communication system for coherent signal transmission.

14   Another object of the present invention is to combine the

15 desirable features of an adaptive feedback equalization (DFE)

16 system with features of a turbo-equalization structure.

17   Yet another object is to provide an augmented high

18 performance iterative receiver algorithm for underwater acoustic

19 telemetry.

20   A feature of one embodiment of the invention combines a

21 decision feedback adaptive equalizer (DFE) with a turbo-equalizer

22 whereby the decision feedback equalizer or variant thereof

23 provides a pre-processing stage for a turbo-equalizer that

24 significantly limits the complexity of the turbo-equalizer.

1	An advantage of the present invention is superior

2	performance as compared to the standard DFE structure.

3	Another advantage is that time or spatial signal diversity

4	can be processed with low complexity within the DFE to provide a

5	single stream of diversity combined symbols which can be

6	processed with a simplified turbo-equalizer construction for use

7	in multichannel transmissions.

8	Yet another advantage of the present invention is that a DFE

9	structure may be utilized therein to take advantage of fractional

10	spacing to help synchronize symbols.

11	Yet another advantage of the present invention is that a DFE

12	structure may be utilized to reduce the extent of the channel

13	response and therefore allow a turbo-equalizer to operate on a

14	much shorter impulse response in order to reduce the complexity

15	thereof.

16	These and other objects, features, and advantages of the

17	present invention will become apparent from the drawings, the

18	descriptions given herein, and the appended claims. However, it

19	will be understood that above listed objects and advantages of

20	the invention are intended only as an aid in understanding

21	certain aspects of the invention, are not intended to limit the

22	invention in any way, and do not form a comprehensive or

23	exclusive list of objects, features, and advantages.

24	Accordingly, the present invention provides a coherent

25	receiver which is operable for use in an underwater telemetry

1 system or for other applications. A coherent receiver in accord

2 with the present invention may comprise one or more elements such

3 as, for instance, one or more data input channels connected to

4 the coherent receiver, and/or a decision feedback equalizer for

5 receiving the one or more data input channels and producing a

6 single stream of pre-processed data at a decision feedback

7 equalizer output, and/or a turbo-equalizer connected to the

8 feedback equalizer output for receiving the single stream of pre-

9 processed data.

10 The coherent receiver may further comprise a plurality of

11 receiver transducers for producing spatially diverse data for the

12 one or more input channels. Alternatively, the coherent receiver

13 may also comprise a single receiver transducer for producing time

14 diverse data for the one or more input channels. In this

15 embodiment, the decision feedback equalizer may also be operable

16 for selectively controlling the total number of the one or more

17 input channels utilized based on error analysis of the diverse

18 data.

19 The coherent receiver may further comprise a training symbol

20 sequence generator and a correlator in communication with the

21 training symbol sequence generator and the decision feedback

22 equalizer wherein the output of the correlator is preferably

23 receivable by the turbo-equalizer.

24 In a preferred embodiment, the turbo equalizer may further

25 comprise an equalizer portion and a decoder portion

1   interconnected for iterative operation. The equalizer portion

2   and the decoder portion may each preferably utilize a maximum a

3   posteriori probability (MAP) algorithm.

4   In operation, the invention comprises a method which may

5   comprise one or more steps such as, for example only, detecting a

6   received signal which may comprise a plurality of data channels,

7   and/or pre-processing the plurality of data channels within a

8   decision feedback equalizer to produce a single output stream of

9   symbol data from the plurality of data channels, and/or post-

10   processing the single output data stream within a single channel

11   turbo-equalizer.

12   The post-processing of the single output data stream may

13   further comprise iteratively equalizing and decoding data from

14   the single output data stream to produce a corrected data output

15   stream and may utilize the MAP algorithm for the steps of

16   iteratively equalizing and decoding.

17   In one embodiment, the method may further comprise

18   mitigating phase jitter in the single output data stream

19   utilizing the decision feedback equalizer.

20   The method may further comprise providing that the received

21   signal comprises a transmitted training symbol sequence, pre-

22   processing the transmitted training symbol sequence to provide a

23   pre-processed training sequence, producing a local training

24   symbol sequence within the receiver, correlating the local

25   training symbol sequence with the pre-processed training sequence

1 to provide channel estimate, and utilizing the channel estimate

2 within the turbo-equalizer.

3

4   BRIEF DESCRIPTION OF THE DRAWINGS

5   A more complete understanding of the invention and many of

6 the attendant advantages thereto will be readily appreciated as

7 the same becomes better understood by reference to the following

8 detailed description when considered in conjunction with the

9 accompanying drawing, wherein like reference numerals refer to

10 like parts and wherein:

11   FIG. 1 is a block diagram schematic of a presently preferred

12 turbo equalizer in accord with the present invention; and

13   FIG. 2 is a block diagram schematic of a presently preferred

14 DFE pre-processor followed by a reduced complexity turbo-

15 equalizer in accord with the present invention.

16

17   DESCRIPTION OF THE PREFERRED EMBODIMENT

18   The present invention provides an augmented high performance

19 iterative receiver algorithm for underwater acoustic telemetry.

20 While the prior art turbo-equalization techniques would have

21 been very complex when used to handle underwater telemetry data,

22 which typically comprises multiple channels, a receiver in accord

23 with the present invention combines a decision feedback adaptive

24 equalizer (DFE) with a turbo-equalizer to produce an improved

1 receiver which has a complexity very close to that of a typical

2 prior art DFE system.

3   Referring now to the drawings and, more particularly to FIG.

4 2, there is shown a block diagram schematic for receiver 10 in

5 accord with the present invention. As described hereinbelow in

6 more detail, decision feedback equalizer or variant 12

7 effectively serves as a pre-processor stage for turbo-equalizer

8 14 in a manner that greatly reduces the complexity for use of

9 turbo-equalization techniques as applied to an underwater

10 acoustic telemetry system with multiple channels. Multi-channel

11 input data 13 may include data received from multiple channels

12 such as, for example, spatially diverse data produced from

13 plurality of transducers received from a single transducer but

14 transmitted by a plurality of transducers. Multi-channel input

15 data 13 may also comprise time diversity transmissions such as,

16 for example, use of a single transmitter and/or single receiver

17 wherein the same data is transmitted multiple times. In the case

18 of the single receiver, due to multipath error, each transmission

19 is affected differently by transmission through the underwater

20 environment and when received is treated as a different channel.

21 The multiple channels of data so produced may be processed

22 simultaneously in the same manner as spatially diverse data

23 received by multiple receivers. Alternately, data may be sent to

24 the single receiver and repeated as necessary. Moreover, as

25 discussed below, the data may be sent a selectable number of

1   times so that the data is repeated only often enough for good

2   reception thereby maximizing data transmission rates.

3   There are a number of advantages to the invention. The

4   performance is superior to the prior art DFE structure, but the

5   complexity is comparable. Moreover, many of the benefits of use

6   of a DFE structure are available. Time or spatial diversity can

7   be used with low complexity within the DFE to provide a single

8   output stream of diversity combined symbols. Also, the DFE can

9   take advantage of fractional spacing to help synchronize symbols.

10   The DFE also reduces the extent of the channel response and

11   therefore allows the turbo-equalizer to operate on a much shorter

12   impulse response reducing the complexity.

13   In the past, the turbo principle of operation has been

14   applied to concatenated codes and to many detection and decoding

15   problems. The idea or principle of turbo coding is to build a

16   strong code by concatenation of simple component codes with an

17   interleaver so that decoding can be performed in steps using

18   algorithms of manageable complexity. In turbo equalization, the

19   channel with inter-symbol interference (ISI) including the

20   transmitter and receiver filters might be regarded as a linear

21   finite state machine, serially concatenated to the channel

22   convolutional encoder. In most cases, a serially concatenated

23   system with an interleaver consists of an outer code, an

24   interleaver permuting the outer code words bits, and an inner

25   finite state machine whose input words are the permuted outer

1   code words. There are different examples for serially

2   concatenated systems. One example of such a scheme is the

3   concatenation of a channel encoder and a non-linear modulator

4   with memory, say a continuous phase frequency-shift keying

5   (CPFSK) modulator. Also, concatenation of a convolutional code

6   and a channel with memory can be considered as a serially

7   concatenated system and we may apply the iterative detection

8   algorithms to this system. Iterative detection schemes are sub-

9   optimum detection algorithms with limited complexity for these

10 systems. The optimum decoding algorithms need a trellis with a

11 huge number of states for which we should consider all system

12 memory. For example, for a system with v memories in a

13 convolutional encoder and with an ISI channel with M memories and

14 an interleaver size N, the optimal decoding algorithms need a

15 trellis with $2^{(v+M+N)}$ states. This potential complexity of a turbo

16 equalizer for an underwater telemetry system is greatly reduced

17 in accord with the teachings of the present invention.

18   A block diagram schematic for one embodiment of turbo

19 equalizer 14 which may be utilized in accord with the present

20 invention is shown in FIG. 1.   Preferably, soft-input soft

21 output (SISO), maximum a posteriori probability (MAP), iterative

22 algorithms are utilized for both channel equalization and

23 decoding, i.e., MAP Equalizer 16 and MAP Decoder 18. Adaptive

24 decision feedback equalizer (DFE) 12 acts as a pre-processor to

25 pre-condition the symbol data which is passed on to turbo-

1   equalizer 14 as indicated at 20. The multi-channel received

2   input data (spatial and/or time diversity) is processed by

3   adaptive decision feedback equalizer (DFE) 12 which also

4   preferably uses a second order phase locked loop for phase jitter

5   mitigation. DFE 12 thereby provides a single symbol stream at 20

6   given any number of received input channels. In this manner, the

7   present invention thereby limits turbo-equalizer 14 to working on

8   a single channel, thereby greatly reducing complexity.

9   Accordingly, in the system of FIG. 1 and FIG. 2, a sequence

10   of synchronized phase compensated values are produced by DFE 12,

11   as indicated at 20, as an input in turbo equalizer 14. MAP

12   equalizer 16 delivers Log values $L^E(u;O)$ about coded bits. After

13   de-interleaving, the channel MAP decoder delivers Log values $L^D(\hat{u})$

14   about information bits and Log values $L^D(c;O)$ about coded bits.

15   Soft-values, preferably in the form of log-likelihood ratios

16   (LLR) values, at the output of MAP decoder 18 consist of an

17   extrinsic and an intrinsic part. The extrinsic part is the

18   incremental information about the current bit obtained through

19   the decoding process from all the other bits in the block. The

20   extrinsic part can be calculated by subtraction of the LLR values

21   as indicated at 19. The extrinsic part, as indicated at 22, is

22   interleaved and fed back to MAP equalizer 16 where the extrinsic

23   part is used as a priori information $L^E(u;I)$ in the new decoding

24   iteration. In a preferred embodiment, the outputs as determined

25   by the iterative processing, which may be hard outputs or soft

14

1 outputs (which are easily converted to hard outputs), are

2 produced at output 28.

3   DFE 12 also has sparsing capability. That is to say that

4 time delayed multipath or channel effects are mitigated by DFE

5 12. Multipath mitigation has the effect of shortening the

6 channel response and limiting the number of important

7 contributing channel coefficients that need to be used by turbo-

8 equalizer 14 thereby lowering complexity. Also, the data from

9 the DFE 12 is fractionally spaced, i.e. 2 samples per symbol,

10 which aids in symbol synchronization for turbo-equalizer 14. The

11 second order phase locked loop structure in the DFE allows for

12 phase jitter mitigation thereby removing the need for estimation

13 of this error from turbo-equalizer 14.

14   The reduced channel estimate for the turbo-equalizer can be

15 obtained by using correlator 26 to cross-correlate the training

16 symbol sequence produced by generator 24 with the corresponding

17 received output symbols from DFE 12 which are the received

18 version of the same information. The reduced channel response

19 at 27 is applied to turbo-equalizer 14.

20   Turbo-equalizer 14 is able to apply the iterative MAP

21 equalization and iterative MAP decoding operating principles as

22 discussed above to correct residual equalization symbol errors

23 that still remain after DFE 12 which acts as a pre-processor

24 stage in hard output 28.

1   One embodiment of the present invention may also be utilized

2   to increase the data rate throughput of prior art time diversity

3   receivers. The present invention is operable to utilize or

4   increase/decrease the number of time diversity data channels,

5   i.e., the number of times the data is resent, in response to

6   analyzing the data packet errors. In this embodiment, if errors

7   are present, only then a subsequent copy of the data packet is

8   resent and/or the number of times the transmitter resends the

9   data packet is controlled whereby the receiver combines the data

10   using time diversity equalization as taught in the prior art

11   discussed hereinbefore. If the data packets are error free,

12   there is no need for additional time diversity or increased time

13   diversity combining. Therefore, on average, the data rate can be

14   increased beyond that possible with constant time diversity

15   processing. In fact, the present invention may or may not be

16   utilized with multichannel data depending on an ongoing analysis

17   of data packet errors and then determining the number of channels

18   required so that the transmitter produces repeated data packets

19   only as needed to obtain accurate reception.

20   In summary, the performance improvement of receiver 10 is

21   due to using the turbo-equalization technique to clean up

22   residual error that is left behind by pre-processing performed by

23   DFE 12.   Time and/or spatial diversity can be used with low

24   complexity within DFE 12 to provide a single stream of diversity

25   combined symbols. Also, DFE 12 can take advantage of fractional

1 spacing to help synchronize symbols. The use of outputs from DFE

2 12 for the training symbol sequence reduces the extent of the

3 channel response and therefore allows turbo-equalizer 14 to

4 operate on a much shorter impulse response thereby reducing the

5 complexity. DFE 12 preferably utilizes a second order phase

6 locked loop to mitigate channel induced phase jitter. This

7 technique can be used to mitigate channel estimation error in

8 turbo-equalizer 14. The new channel estimate for turbo-equalizer

9 14 may be provided by the correlation of the known training

10 symbol sequence and DFE 12 unquantized symbol output.

11   Many additional changes in the details, components, steps,

12 algorithms, and organization of the system, herein described and

13 illustrated to explain the nature of the invention, may be made

14 by those skilled in the art within the principle and scope of the

15 invention. It is therefore understood that within the scope of

16 the appended claims, the invention may be practiced otherwise

17 than as specifically described.